Field Assisted Electron Emission for Electrical Propulsion of Nano Satellites

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ABSTRACT

The micro and nano satellites are expected to play a major role in research, communication, exploration and optimal use of our natural resources and protection of environmental resources. India due to its globally cost competitive launch capability is expected to be a key enabler of satellite launches. These satellites also provide an affordable platform for academic engagement, enabling students to be part of the satellites, payload or subsystem development activity. If these satellites life has to be extended one of the key capability could be compact lightweight propulsion system. Under this R& D an effort is to develop a Field Emission Electric Propulsion (FFEP) system using nanocarbons as a field emission thrusters for the intended purpose to provide attitude control and acceleration of the nano satellite. The novel nanocarbons were developed in the laboratory as a field emission source. The relevant experiments are conducted using customized systems, the DC plasma, the Cathodic arc for material growth. To understand, improve and characterize the field emission properties of nanocarbons, the NSOM (ALPHA 100RAS) for Raman analysis & AFM, the surface morphology and composition were studied using SEM (SU-1500 HITACHI), and the electrical and electronic properties were measured using Keithly Semiconductor device analyzer.

Keywords: Field Emission Electric Propulsion (FEEP); Cathodic arc system; DC Plasma; Nanocarbons; NSOM; SEM (SU-1500 HITACHI).

1. INTRODUCTION

In the ear of Information, & Communication Technology (ICT) and Internet of Things (IoT) satellites are expected to increasingly play a significant role. Further the advancement in technology today allows the satellite to become smaller and yet carry greater capacity and capability payloads. In the next 10 years literally close to 300+ satellites will be launched every year. For enhancing internet services Airbus and one web expect to launch over 900 satellites, while Samsung is expected to launch over a 1000 micro satellites. Indian Space Research Organization (ISRO) which has launched over 5 student satellite is expected to launch 5 more soon. ISRO is creating special nano and micro satellite module shells ready for universities to design their application specific payloads, to be housed in these modules shells and then be launched. The area of applications for these satellites include, Communication, Earth Observation & Monitoring for environmental and other reasons, Mapping & Navigation, Scientific Research & Exploration, Defense, Surveillance, and Security. The small satellite industry currently about $ 2.2 Billion in 2016 is expected to reach $ 5.2 Billion by 2021 [1-3].

A key feature that would enable these nano, micro and mini satellites to further extend their capability could be a compact, energy efficient and appropriate type of fuel based propulsion system. Typically there are multiple ways of propulsion that can be adopted including Hall thrusters, Ion thrusters, chemical propulsion, and Field Emission Electrical Propulsion (FEEP) [4-11]. Electric propulsion (EP) has emerged as relatively a key form of advanced propulsion and it is rapidly becoming the standard choice, because of its very high mass eciency. The eciency is measured in secondsof specic impulse (ISP); it is the number of seconds for which one pound of propellant will produce one pound of thrust. The Various forms of EP systems have different ISP values of thousands of seconds, whereas standard chemical propulsion which have around 400 seconds [3, 4].

The key element of these Field assisted electron emitter based electrical propulsion is the emitter array. Wide range of electron emitter arrays including those based on Spindt tips made of silicon & metal tips, transfer mold emitters with carbon over coats, flat emitters based on wide range of carbons including carbon nanotubes, nano-diamonds, nanocrystalline carbon, graphene, tetrahedral amorphous carbon based emitter and nanocluster carbon have been reported including by co-authors of the paper[11-20]. These emitters are considered for their properties and functionalities including high aspect ratio, good electrical conductivity, controllability and scalability as the case may be. In addition they possess high thermal conductivity, mechanical strength and chemical stability. Thus reported in this paper is the study of nanocarbons based Field Emission Electrical Propulsion (FEEP) system.

The FEEP provides provision for directional control, altitude control, acceleration for small satellites and possibility of extension of life of the satellite. For the satellites in the orbit, the mass of fuel or structures containing that fuel contributes almost 50% of the total orbited mass. Hence the extension of life come with cost in terms of weight and reduction in functionality or capabilities of the satellites. Thus in case of small satellites Electric propulsion and especially FEEP offer huge benefits. They offer multiple benefits including greater e�ciency, and corresponding reduction in volume and mass of required propellant. If the fuel mass is reduced, additional payload can be incorporated and capability of the satellite can be increased. [6-10]. However EP is restricted in their mass throughput and total impulse, because of its high power demands. They also produce very little thrust from μN to 10s of Newton's of force, hence electric propulsion is used as a secondary propulsion system. Thus presented in this paper is a brief overview of small satellite technology, propulsions systems for the same needed for extend life and an initiative to create affordable indigenous capability in an academic institution to develop complete FEEP including, creating design capability, consideration of material and process equipment, electron emitter, emitter and arrays, their characterization facility, and control electronics. The same electron emitters can also be used in a wide range of vacuum nanoelectronics applications including lighting, compact X-ray sources, MW & THz sources and medical instrumentation [13-14].

1.1 Types of Electric Propulsion (EP)

Electric propulsion (EP) can be broadly classified in to Ion/plasma drives and nonion drives. Ion/Plasma drives uses electrical energy to obtain thrust from the propellant carried with the spacecraft. [5-12]. Shown in figure 1 is the broad classification of Electric Propulsion (EP).

It may be broadly classified into 3 categories:

a. **Electro thermal propulsion:** the propellant is electrically heated, then expanded thermo dynamically through a nozzle to generate the thrust

b. **Electrostatic propulsion:** it accelerate the ionized propellant particles through the application of electric field.

c. **Electromagnetic propulsion:** the current driven through a propellant plasma interacts with an internal or external magnetic field to provide a stream-wise body force. It can produce a range of exhaust velocities and payload mass fractions an order of magnitude higher than that of the most advanced chemical propulsion systems.

1.2 Field Emission Electrical Propulsion (FEEP)

It is the era of small satellites. Most of the satellites ranging from small-to-medium size are used in the task such as attitude control, fine pointing, drag makeup and orbit maintenance adopt Filed Emission Electrical Propulsion, due to its significant mass savings and performance enhancement compared to other thrusters.

Field Emission electrical Propulsion falls into to the category of electrostatic propulsion. Field Emission is a process of using strong electric field to produce the spray of charged ions and /or droplets. FEEP thrusters are an effective form of electric propulsion for small satellites. It uses a highly energetic ion beam to generate thrust in a very efficient and controllable manner. It provides micro- to milli-Newton's of force. LISA (Laser Interferometer Space Antenna),LISA pathfinder and Microscope and some of the satellites where FEEP electric propulsion is used.

In general FEEP devices have a liquid propellant, which is driven by capillary action to very thin slit which will be few microns wide. A strong electric field is applied, which will tear ions away from the liquid propellant surface. The ions are accelerated by the same electric field and are ejected with the velocity of 80-100Km/s depending upon the type of the propellant used. The total thrust FEEP can provide range from 0.1 to 100μN.The basic structure of FEEP system consists of an Emitter, an Accelerator and Neutralizer.

The accelerating electrode (accelerator) is placed directly in front of the emitter. The electrode consists of a metal (stainless steel is usually used) plate and the two sharp blades are machined. A strong electric field is produced by the application of a high voltage difference between the emitter and accelerator. The actual thrust is produced by exhausting a propellant atoms, produced by field evaporation at the tip of the emitter. At this point, due the combined effects of the electrostatic force and surface tension, local instability is experienced by the free surface of the liquid metal. Thus creating Taylor cone protruding outwards due to space charge. At the tip the atoms are ionised and accelerated by the existing electric field. An external source of electrons (neutralizer) provides negative charges to maintain electrical neutrality.

Types of Electric Propulsion:

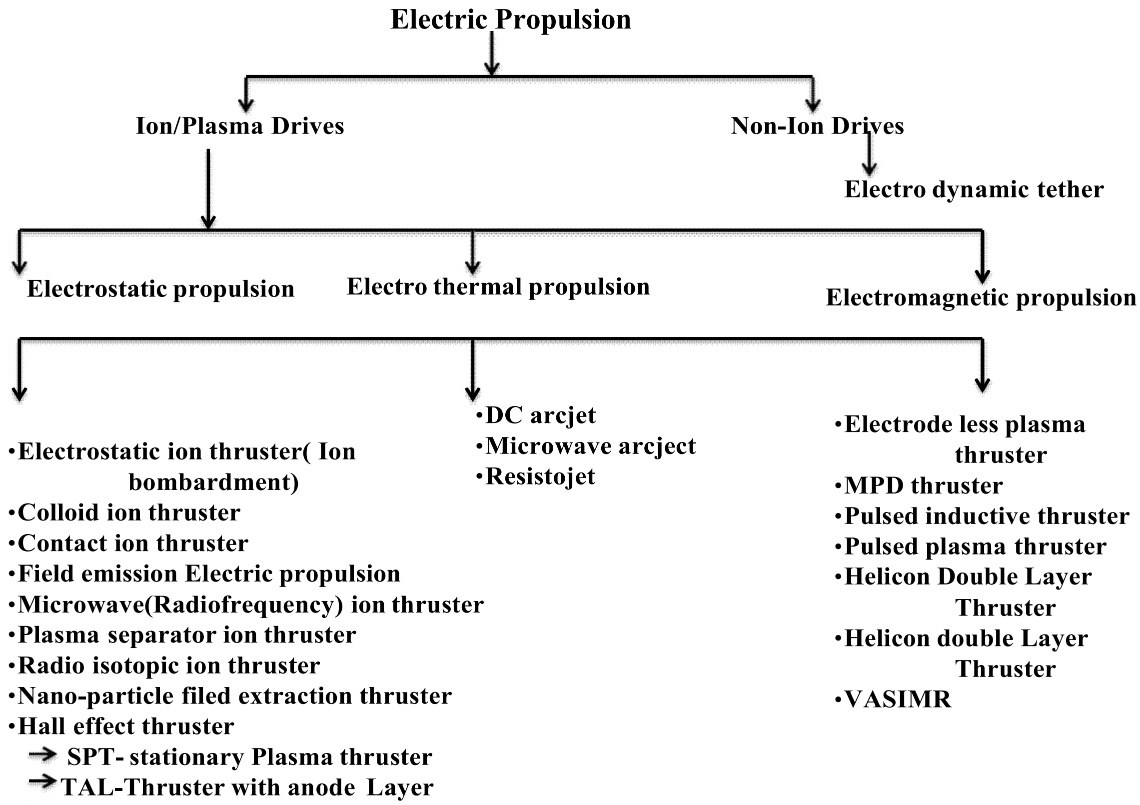

Figure 1. Broad classification of Electric Propulsion (EP) technologies

A. FEEP Propellants:

The Alkali metals are considered as the best propellant for FEEP thrusters. They are selected based on high atomic mass, good wetting capabilities (to maintain propellant flow to ion emission site).Some of the propellants considered for FEEP is listed in the table 1.

Table 1: FEEP Propellants

Propellant	Melting Point
Cesium	28.5°C
Rubidium	38.9 °C
Indium	156°C
Gallium.	30°C

B. Drawbacks of FEEP:

FEEP thrusters can produce specific impulses above 10,000 seconds at electrical efficiencies exceeding 90% using melted metal liquid propellants. However, these FEEPs require footprints for make needle-like emitters that are many of times wider than the actual niddle tips. This will rule out the possibility of their potential for being scaled-up to multi-kW power levels is doubtful.

The concept of developing field emission cathodes using nanocarbons for the FEEP thrusters is highly scalable technology. The nanocarbons can improve the overall propulsion system performance. The Nanocarbon cathodes are most suitable for low-power and small satellites since large fraction of the propellant is wasted on the standard FEEP technology.

C. Need for Designing a FEEP Using Nanocarbon based Emitters:

To reduce the cost associated with single large spacecraft, the development of micro/nano/pico satellites has become necessary. The small sized satellites require less electrical power, smaller solar arrays on the platform, smaller battery, less thermal dissipation etc. However the smaller sized micro/nano/pico satellites also have shorter life span, due to the absence of built in propulsion systems. Now choosing an appropriate propulsion system for these small satellites is a bigger challenge.

Light weight propulsion system would be ideal for small satellites. Electrical propulsion systems are chosen above chemical propulsion systems for such applications, since it can reduce the propellant by mass, thereby reducing the size of the propulsion system and in turn reducing the overall size of the satellite. For the development of micro scale thrusters like FEEP, thruster requires electron sources for ion beam neutralization.

The Field emission electric propulsion (FEEP) is based on the concept of electrostatic propulsion. It is of great interest because of its unique features: 1µN to 1mN thrust range, capability of switch on/switch off instantaneously and high-resolution throttle ability. This enables accurate thrust modulation in continuous and pulsed modes. While designing an electrical propulsion system for Nano satellites parameters likeΔV, specific impulse, thrust, and minimum impulse bit are considered. Hence FEEP requires an efficient emitter for its better performance. The nanocarbons exhibit high electrical and thermal conductivity, high aspect rations, good field emission, high extraction efficiency, high durability and low cost manufacturing. [12]

2. EXPERIMENTAL SETUP

Field emitter materials should have a low work function, good electrical and mechanical properties. It should also withstand the extremely high electrical stresses. Apart from these capabilities it should also be suited for micro fabrication technologies and should possess good work function and geometric factors like: aspect ratio play a significant role in establishing the emitter characteristics. The Nano carbons are used for FEEP emitters because they have high aspect ratio, they can operate at lower temperatures with less power- without using on-board propellant. This would allow the longer mission for satellites thereby reducing the weight of the propulsion system and satellite altogether, various manifestations of Nano carbon includes carbon nanotubes, nanostructured graphite, nano diamond, Nano walls, Nano cluster carbon, diamond like carbon (DLC) and tetrahedral amorphous carbon (taC), which are building blocks for various Nano electronic devices and nanotechnology applications [11-21].

All the required factors as a field emitters cannot be easily controlled or implemented using single deposition process. This calls for multiple processes, taking into consideration of the above requirements for field emitters, it was possible to develop a novel, room temperature grown, nanocarbon based electron emitter, suitable for most vacuum micro/nano electronic applications.

The nanocarbon films were deposited using custom designed systems: DC plasma CVD & Cathodic arc. The films were deposited on substrates (n+) silicon/glass. The gases used CH4, N2, H2 and He. The Cathodic arc deposition of nanoclusters and tetrahedral amorphous carbon were carried out at room temperature with deposition pressure ranging from 10-6 and 10-1 Torr. The CNT growth was carried out under deposition pressure ranging from 10-3 & 10-2 Torr at 300°C by Plasma CVD process. The Witec NSOM/AFM/Raman system was sued to measure the surface morphology, the composition and even the emission uniformity measurements.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The growth of the nanocarbon thin films for Cathodic Arc system are influenced by parameters such as: Arc voltage, Arc current, Arc-type, substrate material, substrate temperature, substrate distance, magnetic field, deposition rate, deposition time, and gaseous environment of the chamber.

The characterization of samples were carried out using NSOM(Near Field Scanning Optical Microscope-ALPHA 300RAS), which is capable of three imaging techniques in a single instrument consists of a High Resolution Confocal Raman Microscopy (CRM), Atomic Force Microscopy (AFM) and Scanning Near field Optical Microscopy (SNOM).

For characterizing the samples an excitation wavelength of 532nm used for Raman analysis and for AFM measurements cantilever with 42N/m & 285 KHz, AC Mode Tapping/Non tapping both the modes (Non-contact/contact Mode) method was implemented. The SEM imaging of the films were carried out using SEM (SU-1500 HITACHI) and conductivity measurements using Semiconductor device analyzer were conducted to study different properties.

The field emission experiments are carried out at a vacuum of about 10-7 Torr. Shown in Figure 2 is the custom designed FE measurement system. The field emission measurements were carried out both in diode and triode configuration. The system consists of a custom designed power supply with provision to change the inputs from 0 to 20KV and a Kiethley Electrometer which also has a inbuilt power supply (1 KV) and currents can be measured from mA to 10-12 A can be measured. The system also has provision to capture image the field emission capability from the window on the top while measuring phosphor based anodes.

It can be seen from the curves that these films exhibit very low emission thresholds lying in the range of 1 to 2 V/µm. However they all do not exhibit the same emission site densities. Shown in figure 4 a), b), c) and d) are the AFM images based on current emission distribution measurements in the case of room temperature grown nanocluster carbon. The AFM measurements carried out at different locations and area considered for measurements is 0.3µm and 0.1µm.

Figure 2: Custom designed FE measurement system fixture inside the Vacuum chamber.

Shown in figure.3 is the typical field emission characteristics of the various Nano carbons films grown using diverse process.

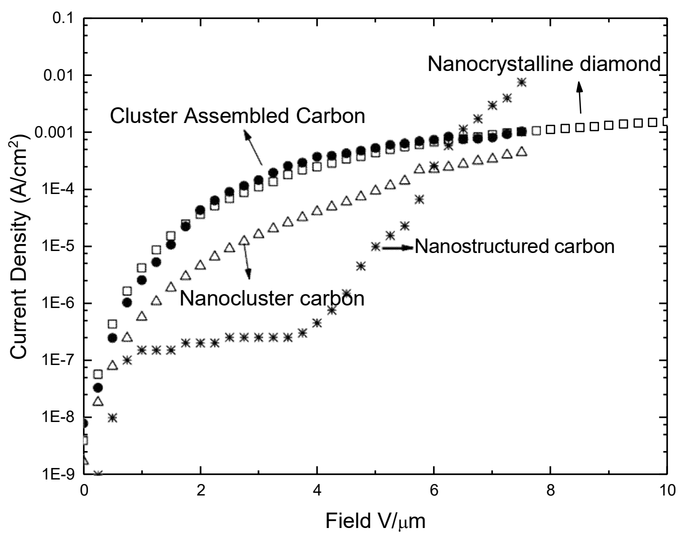

Figure 3: Typical field emission J-E curves from various nanocarbon based materials [17-21]

It may be seen from the film that at closer proximity Nano clusters are visible and also the change in intensity of the brightness shows the difference in current emission. However as the tip moves away from the sample surface the emission looks more uniform. Thus efforts are on to use this as a basis and compare the same with the simulated emission distribution and array configuration. Most FEEP have used metal or silicon based Spindit tips and a few have used CNT arrays [6, 7, 11, 13, 14]. Based on the Emission distribution and actual measured emission current, the simulation of emission arrays indicate that the room temperature grown Nano carbons need to be further improved for current densities. The details simulation and analysis is being communicated. But based on the current data it may be mentioned that these samples with conditioning and optimization could be used for field emission application in FEEPs. The added advantage of the Nano cluster carbon films grown using the Cathodic arc is that it can also be subjected to standard plasma etching process for patterning the emitters. Thus with further studies we expect it would be feasible to develop indigenous and affordable FEEPs for propulsion of nano and micro satellite.

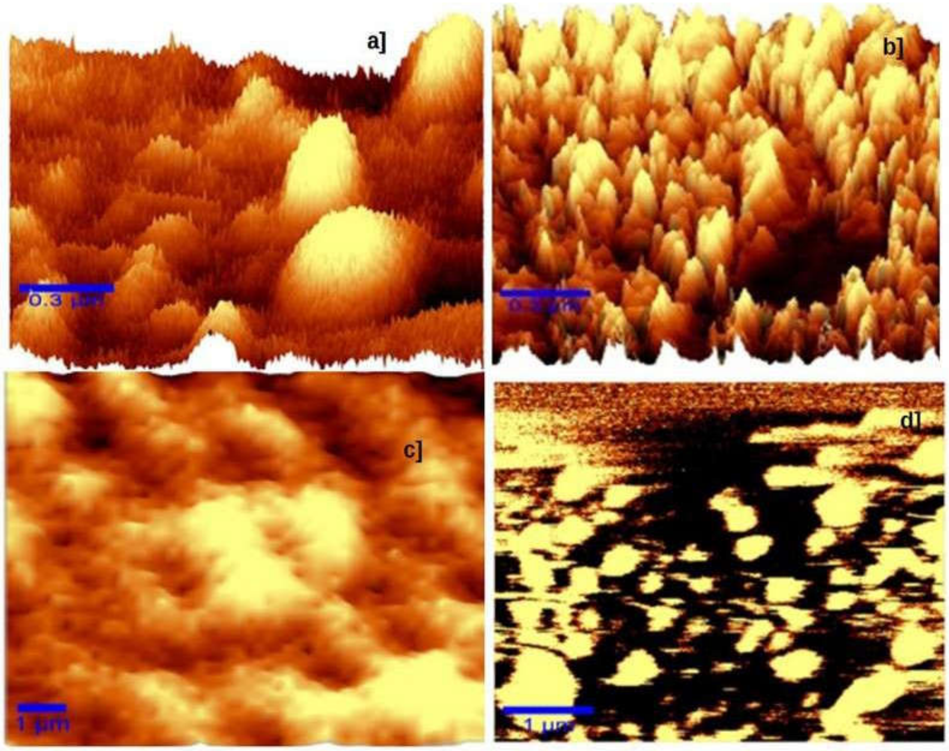

Figure 4: AFM based emission site distribution measurement of room temperature grown Nanocluster carbon films.

4. CONCLUSION

In summary this paper reports a brief review of the global and Indian small satellite technology scene and the opportunities and the need for compact and small propulsion system for extending the life of these satellites. Also presented is a brief comparison of various types of propulsion technology available for small satellites and the possible advantage of field assisted electron emitter based FEEP systems. Presented next is how the creation of an indigenous capabilities of large area flexible electronics is being leveraged to create a complete eco system for small satellite developments, from design and development of the Pico and nano satellites, the pay loads, to even incorporation of FEEP propulsion for extended life of satellites. As RVCE was part of the team that was involved in the launch of the India's first Pico satellite with ISRO support. Now the Macro electronic Centre of Excellence is being used to grow nano carbons and also characterize the same using indigenously developed process and characterization facility. The preliminary experimental characterization demonstrates that with further development and conditioning the electron emitters can be used for obtaining optimal emission current required for the generation of the thrust.

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